

# Compact stars within an asy-soft quark-meson-coupling model

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We investigate compact star properties within the quark meson coupling model (QMC) with a soft symmetry energy density dependence at large densities. In particular, the hyperon content and the mass/radius curves for the families of stars obtained within the model are discussed. The hyperon-meson couplings are chosen according to experimental values of the hyperon nuclear matter potentials, and possible uncertainties are considered. It is shown that a softer symmetry energy gives rise to stars with less hyperons, smaller radii and larger masses. Hyperon-meson couplings may also have a strong effect on the mass of the star.

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## I. INTRODUCTION

In the last years important efforts have been done to determine the density dependence of the symmetry energy of asymmetric nuclear matter (see the reviews [1–3] and references therein). Correlations between different quantities in bulk matter and finite nuclei have been established. For instance, the correlation between the slope of the pressure of neutron matter at  $\rho = 0.1 \text{ fm}^{-3}$  and the neutron skin thickness of  $^{208}\text{Pb}$  [4, 5], or the correlation between the crust-core transition density and the neutron skin thickness of  $^{208}\text{Pb}$  [6] are well determined. Presently, there also exist different experimental measurements that constrain the saturation properties of the symmetry energy [7].

The quark-meson-coupling (QMC) model [8–10] is an effective nuclear model that takes into account the internal structure of the nucleon explicitly. Within the QMC model, matter at low densities and temperatures is a system of nucleons interacting through meson fields, with quarks and gluons confined within MIT bags [11]. For matter at very high density or temperature, one expects that baryons and mesons dissolve and that the entire system of quarks and gluons becomes confined within a single, big, MIT bag. Within QMC it is possible to describe in a consistent way both nucleons and hyperons [12]. The energy of the baryonic MIT bag is identified with the mass of the baryon and is obtained self-consistently from the calculation. It is important to stress that within the QMC model the coupling of hyperons to the  $\sigma$ -meson is fixed at the level of the saturation properties of the equation of state (EOS). Hypernuclei properties [13–16] will then allow the determination of the coupling of hyperons to the isoscalar-vector meson without any ambiguity except for the uncertainty on the experimental hypernuclei data. Within the non-linear Walecka models (NLWM) this is not possible and some other constraint must be imposed, such as using the SU(6) symmetry to fix the

hyperon-vector meson couplings [17].

Recently, new data on neutron stars have been obtained [18, 19] that theory should explain, namely, the large value  $1.97 \pm 0.04 M_{\odot}$  of the recent mass measurement of the binary millisecond pulsar PSR J16142230 [18], and the empirical EOS obtained by Steiner *et al.* from a heterogeneous set of seven neutron stars with well-determined distances [19] which predicts quite small radii. These last results, however, should still be considered with care because there are many uncertainties involved.

The symmetry energy at saturation is quite well established, however, the density dependence of the symmetry energy is not so well known and different models predict a wide range of values for the symmetry energy slope at saturation. Although the symmetry energy slope of QMC at saturation (94 MeV [20]) is within the range of values compatible with experimental observations [21], most of the experimental observables that have been proposed to obtain a measure of the symmetry energy slope, predict smaller slopes [7], which could be as low as 30 MeV. Moreover, the large value of the QMC slope prohibits the prediction of small radii as the ones indicated by the empirical EOS [19].

In [20] we have introduced the  $\delta$ -meson in the QMC model and have studied its effect on the density dependence of the symmetry energy and subsaturation instabilities of nuclear matter. However, the introduction of the  $\delta$ -meson gives rise to a stiffer symmetry energy and this mechanism will not allow us to obtain a softer symmetry energy for the QMC.

In the present study we consider an extension of the QMC that includes a nonlinear term involving the  $\omega$  and  $\rho$  mesons. This term affects the isovector channel of the QMC equation of state, namely the density dependence of the symmetry energy [6, 22], and choosing the coupling constant adequately it is possible to correct the stiff behavior of the symmetry energy at large densities in the

QMC model.

Stellar matter within the modified QMC model will be studied. We expect that smaller values of the symmetry energy slope will give rise to smaller star radii: this has been shown both for nucleonic stars [6, 23] and for hyperonic stars [24]. In particular, we want to investigate how the hyperon content of a compact star is affected by the density dependence of the symmetry energy. This was recently done within the NLWM including the nonlinear  $\omega\rho$  term [24] and it was shown that the hyperon content could be affected by the density dependence of the symmetry energy, and that the radius of stars with a mass 1-1.4  $M_\odot$  increases linearly with the slope, while the mass is not affected. However, the QMC model gives rise to a softer EOS and generally predicts smaller hyperon fractions in stellar matter. This could affect the behavior of the star properties and its relation with the slope of the symmetry energy.

The paper is organized as follows: in section II an extension of the QMC model to include the  $\omega - \rho$  coupling is discussed, in section III results are presented and discussed and the final conclusions are drawn in the last section.

## II. THE QUARK-MESON COUPLING MODEL

In what follows we present a review of the QMC model and its generalization to include the isoscalar-isovector  $\omega - \rho$  coupling.

In the QMC model, the nucleon in nuclear medium is assumed to be a static spherical MIT bag in which quarks interact with the scalar ( $\sigma$ ) and vector ( $\omega$ ,  $\rho$ ) fields, and those are treated as classical fields in the mean field approximation (MFA) [8, 9]. The quark field,  $\psi_{q_i}$ , inside the bag then satisfies the equation of motion:

$$\left[ i \not{\partial} - m_q^* - \gamma^0 (g_\omega^q \omega_0 + g_\rho^q t_{3q} b_{03}) \right] \psi_{q_i} = 0, \quad (1)$$

where  $q = u, d, s$ ,  $m_q^* = m_q^0 - g_\sigma^q \sigma$  with  $m_q^0$  the current quark mass, and  $g_\sigma^q$ ,  $g_\omega^q$  and  $g_\rho^q$  denote the quark-meson coupling constants. The energy of a static bag describing baryon  $i$  consisting of three quarks in ground state is expressed as

$$E_i^{\text{bag}} = \sum_q n_q \frac{\Omega_{q_i}}{R_i} - \frac{Z_i}{R_i} + \frac{4}{3} \pi R_i^3 B_N, \quad (2)$$

where  $\Omega_{q_i} \equiv \sqrt{x_{q_i}^2 + (R_i m_q^*)^2}$ ,  $R_i$  is the bag radius of baryon  $i$ ,  $x_{q_i}$  is the dimensionless quark momentum,  $Z_i$  is a parameter which accounts for zero-point motion of baryon  $i$  and  $B_N$  is the bag constant. The effective mass of a baryon bag at rest is taken to be  $M_i^* = E_i^{\text{bag}}$ . The equilibrium condition for the bag is obtained by minimizing the effective mass,  $M_i^*$  with respect to the bag radius

$$\frac{dM_i^*}{dR_i^*} = 0. \quad (3)$$

We have considered  $B_N^{1/4} = 211.30306$  MeV and  $R_i = 0.6$  fm. The unknowns  $Z_i$  are given in [10].

### A. QMC with coupled $\omega - \rho$ fields

The consideration of a coupling between the isoscalar and isovector fields is carried out much like in the manner it was performed in [6]. A note is however on demand: we start out from quarks, which find themselves confined in a bag [11], and the boundary conditions for achieving confinement hold the same. The relevant changes (of couplings) and fittings (to the symmetry energy) are done otherwise for hadronic matter. The total energy density of the nuclear matter then reads

$$\begin{aligned} \varepsilon = & \frac{1}{2} m_\sigma^2 \sigma^2 - \frac{1}{2} m_\omega^2 \omega_0^2 - \frac{1}{2} m_\rho^2 b_{03}^2 - g_\omega^2 g_\rho^2 \Lambda_v b_{03}^2 \omega_0^2 \\ & + g_\omega \omega_0 \sum_B x_{\omega B} \rho_B + g_\rho b_{03} \sum_B x_{\rho B} t_{3B} \rho_3 \\ & + \sum_B \frac{2J_B + 1}{2\pi^2} \int_0^{k_{FB}} k^2 dk [k^2 + M_B^{*2}]^{1/2}, \end{aligned} \quad (4)$$

where  $t_{3B}$  is the isospin projection of baryon  $B$ . For the nucleons we take  $x_{\omega B} = x_{\rho B} = 1$ . The corresponding coefficients for the hyperons will be discussed later. In the above expression for the energy density, we have introduced the  $\omega - \rho$  couplings. The chemical potentials, necessary to define the  $\beta$ -equilibrium conditions, are given by

$$\mu_B = \sqrt{k_{FB}^2 + M_B^{*2}} + g_\omega \omega_0 + g_\rho t_{3B} b_{03}.$$

In the above expressions the mean fields for mesons are determined by the equations

$$\frac{\partial \varepsilon}{\partial \sigma} = 0, \quad \omega_0 = \frac{g_\omega}{m_\omega^{*2}} \sum_B x_{\omega B} \rho_B, \quad b_{03} = \frac{g_\rho}{m_\rho^{*2}} \sum_B x_{\rho B} t_{3B} \rho_3,$$

where  $m_\omega^{*2} = m_\omega^2 - 2\Lambda_v g_\rho^2 g_\omega^2 b_{03}^2$  and  $m_\rho^{*2} = m_\rho^2 - 2\Lambda_v g_\rho^2 g_\omega^2 \omega_0^2$ , and  $g_\omega = 3g_\omega^q$  and  $g_\rho = g_\rho^q$ .

The model parameters are obtained by fitting the nucleon mass and enforcing the stability condition for the bag in free space. The desired values of  $E_N \equiv \epsilon/\rho - M = -15.7$  MeV at saturation  $\rho = \rho_0 = 0.15$  fm $^{-3}$ , are achieved by setting  $g_\sigma^q = 5.981$ ,  $g_\omega = 8.954$ . We take the standard values for the meson masses, namely  $m_\sigma = 550$  MeV,  $m_\omega = 783$  MeV, and  $m_\rho = 770$  MeV. The couplings  $g_\rho$  and  $\Lambda_v$  are determined so that  $\mathcal{E}_{\text{sym}} = 23.27$  MeV at  $\rho = 0.1$  fm $^{-3}$  ( $k_F \sim 1.14$  fm $^{-1}$ ). The parameters  $g_\rho$  and  $\Lambda_v$  are listed in Table I.

## III. RESULTS AND DISCUSSIONS

Before applying the modified QMC model to the study of stellar matter we discuss its properties at saturation and subsaturation densities.

TABLE I. Nuclear matter properties of the models used in the present work. All quantities are taken at saturation, where  $B/A=15.7$  MeV and the compressibility  $K_0 = 290$  MeV.  $\rho_t$  and  $Y_{p,t}$  are the density and proton fraction at the crust-core transition estimated from the thermodynamical spinodal section.

Model	$\Lambda_v$	$g_\rho$	$\mathcal{E}_{sym}$ (MeV)	$L$ (MeV)	$\rho_t$ (fm $^{-3}$ )	$Y_{p,t}$
QMC	0	8.8606	33.70	93.59	0.076	0.022
QMC $\omega\rho$	0.01	8.9837	33.02	84.99	0.079	0.024
	0.02	9.1122	32.43	77.35	0.081	0.025
	0.03	9.2463	31.88	70.55	0.083	0.026
	0.05	9.5335	30.87	59.03	0.089	0.029
	0.10	10.3869	27.78	39.04	0.098	0.033
NL3 [25]	0	8.9480	37.34	118.30	0.065	0.021
TW[26]	0	7.3220	32.76	55.30	0.084	0.038

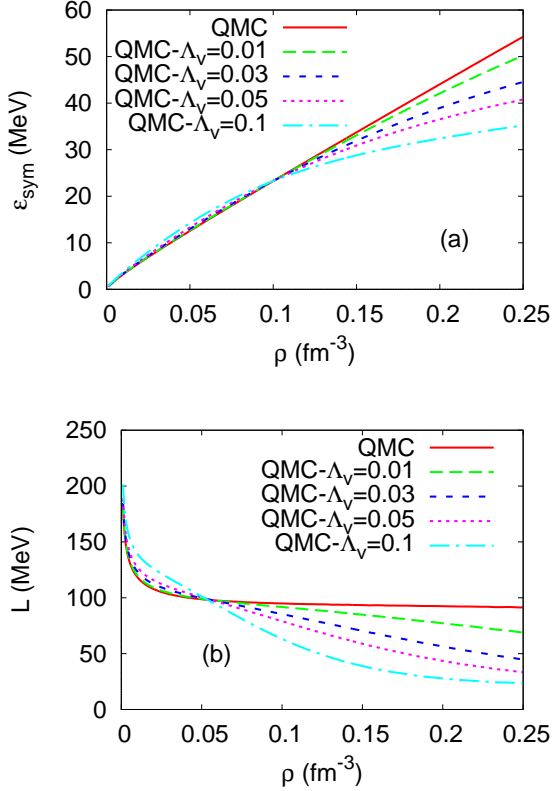


FIG. 1. (Color online) Symmetry energy (a), its slope parameter  $L = 3\rho_0 \mathcal{E}'_{sym}$  (b), and curvature  $K_{sym}$  for QMC and QMC $\omega\rho$  for different values of the coupling  $\Lambda_v$ .

The saturation properties of nuclear matter for all the QMC models considered in the present work are shown in Table I. For comparison, we also include the properties of two well known relativistic nuclear models NL3 [25] and TW [26]. Except for the the symmetry energy of the QMC $\omega\rho$  model with  $\Lambda_v = 0.1$ , which could be a bit too low, both the symmetry energy and its slope

$L = 3\rho_0 \partial \mathcal{E}_{sym} / \partial \rho$  of all the parametrization are well within the experimental constraints coming from different sources [7].

Fig.1 shows the dependence on the density of the symmetry energy  $\mathcal{E}_{sym}$  and its slope for the different parametrizations of the non-linear  $\omega - \rho$  term. The symmetry energy is given by

$$\mathcal{E}_{sym} = \frac{k_F^2}{6\epsilon_F^2} + \frac{\rho}{8} \frac{g_\rho^2}{m_\rho^{*2}} \quad (5)$$

where  $\epsilon_F = \sqrt{k_F^2 + M_0^{*2}}$  and  $M_0^*$  is the nucleon effective mass in symmetric nuclear matter. The symmetry energy within QMC shows a rather linear behavior with density. This is a feature of many NLWM models. The nonlinear  $\omega\rho$  term changes the density dependence of the symmetry energy, and, as a result, the symmetry energy of the QMC $\omega\rho$  (Fig.1(a)) becomes softer at higher densities. This is confirmed by the slope parameter  $L$ , plotted in Fig. 1(b): above  $\sim 0.06$  fm $^{-3}$ ,  $L$  becomes smaller the larger the coupling  $\Lambda_v$  is. However, below  $\rho = 0.1$  fm $^{-3}$  the symmetry energy is larger in the models with a larger  $\Lambda_v$  and this has important effects on the properties of the crust-core transition.

#### A. Crust-core transition

The QMC $\omega\rho$  presents larger instability regions than QMC at subsaturation densities and large isospin asymmetries. The larger the magnitude of the coupling  $\Lambda_v$  the smaller the slope  $L$  and the larger the instability region. The same behavior was obtained in [22] for NL3 $\omega\rho$  and is contrary to the one obtained in [20] with the inclusion of the  $\delta$ -meson in the QMC model. In [27] the effect of the slope  $L$  on the spinodal surface at large asymmetries was discussed and it was shown that larger values of  $L$  give rise to smaller spinodal regions at large asymmetries, where matter is closer to neutron matter. Neutron matter pressure is essentially proportional to the slope  $L$  and, therefore, a larger  $L$  corresponds to a harder EOS. The crust-core transition densities are shown in Table I and it is seen that they increase with the increase of the  $\omega - \rho$  coupling. The proton fraction at the transition density also tends to increase QMC gives a higher transition density than the one obtained within NL3. For  $\Lambda_v$  in the range 0.03-0.05 we get results similar to TW, as expected due to the values of  $L$ .

In the inner crust of a compact star, matter is not homogeneous, and is characterized by different isospin contents for each phase, i.e., the clusterized regions are more isospin symmetric than the surrounding nuclear gas, the so-called isospin distillation [28, 29]. The extension of the distillation effect is model dependent and it has been shown that NL3 and other NLWM parameterizations lead to larger distillation effects than the density dependent hadron models [30–32]. In Fig.2 we show the ratio of the proton versus the neutron density fluctuations corresponding to the unstable mode. This ratio

defines the direction of the instability of the system. We show the results for two proton fractions  $Y_p = 0.3$ , and  $0.05$ , for the sake of studying the effectiveness of the models in restoring the symmetry in the liquid phase in two situations of interest for compact stars:  $\beta$ -equilibrium matter with and without trapped neutrinos. The  $\omega - \rho$  coupling decreases the  $\delta\rho_p/\delta\rho_n$  ratio, as already obtained in [22] for NL3 $\omega\rho$ , although in this last work a dynamical calculation was performed. Comparing with the result reported in [30] we conclude that: a) QMC behaves differently from NLWM models such as NL3. For these models the ratio of the proton versus the neutron density fluctuations increases with the density, while for QMC after a maximum obtained at  $\rho \sim 0.02 \text{ fm}^{-3}$ , this ratio decreases and more strongly if  $\Lambda_v$  is large; b) QMC presents a behavior similar to the one of relativistic models with density dependent couplings such as TW, however, the decrease of the distillation effect with density is not so strong [30, 33], even for the largest  $\Lambda_v$  coupling we have considered.

### B. Neutron stars

Having discussed the behavior of the generalized QMC model at subsaturation densities, we now turn to the

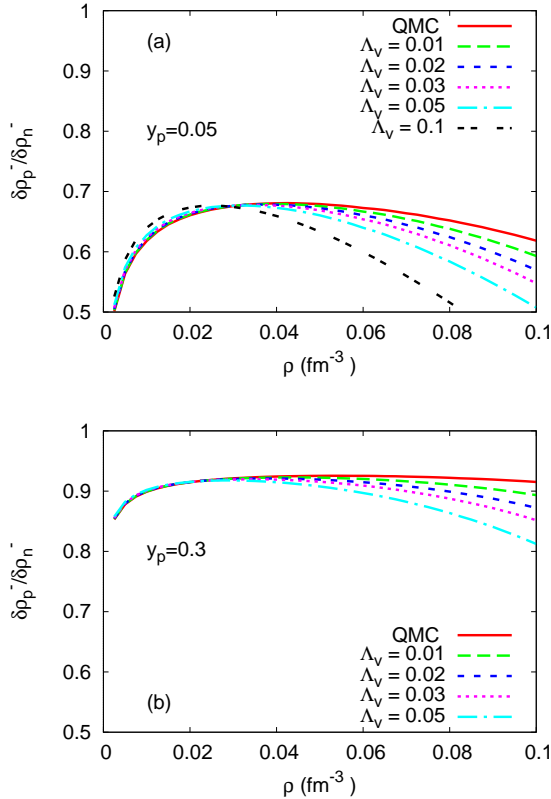


FIG. 2. (Color online) Direction of instability for  $Y_p=0.05$  (a), and  $0.3$  (b).

main topic of the present work and discuss the stellar properties obtained in the present approach. The composition of the stellar matter is determined by the requirements of the charge neutrality and chemical equilibrium under the weak processes

$$B_1 \rightarrow B_2 + l + \bar{\nu}_l; \quad B_2 + l \rightarrow B_1 + \nu_l \quad (6)$$

where  $B_1$  and  $B_2$  are baryons,  $l$  is a lepton. The EOS which depends on the chemical potentials is now modified according to [12], so that the lowest eight baryons are taken into account. As we restrict ourselves to zero temperature, no trapped neutrinos are considered, but the electrons and muons are considered so that charge neutrality and  $\beta$ -equilibrium can be enforced. The hyperon couplings are not relevant to the ground state properties of nuclear matter, but information about them can be available from the levels in hypernuclei [13, 34–38]. Note that the  $s$ -quark is unaffected by the sigma and omega mesons i.e.  $g_\sigma^s = g_\omega^s = 0$ .

In QMC the couplings of the hyperons to the  $\sigma$ -meson do not need to be fixed because the effective masses of the hyperons are determined self-consistently at the bag level. Only the  $x_{\omega B}$  and  $x_{\rho B}$  have to be fixed. The coupling strength of the  $\rho$  meson is given by the isospin of the baryon, and we obtain  $x_{\omega B}$  from the hyperon potentials in nuclear matter,  $U_B = -(M_B^* - M_B) + x_{\omega B} g_\omega \omega_0$ , for  $B = \Lambda, \Sigma$  and  $\Xi$  to be -28 MeV, 30 MeV and -18 MeV, respectively. We find that  $x_{\omega\Lambda} = 0.743$ ,  $x_{\omega\Sigma} = 1.04$  and  $x_{\omega\Xi} = 0.346$ .  $x_{\rho B} = 1$  is fixed for all the baryons. However, while the binding of the  $\Lambda$  to symmetric nuclear matter is well settled experimentally [14], the binding values of the  $\Sigma^-$  and  $\Xi^-$  still have a lot of uncertainties [16]. We, therefore, test the effect of the coupling to the cascade and show results also for  $V_\Xi = -10$  and  $0$  MeV. In fact, measurements from the production of  $\Xi$  in the  $^{12}\text{C}(K^-, K^+)_{\Xi}^{12}\text{Be}$  are compatible with a shallow attractive potential  $V_\Xi \sim -14$  MeV [15]. We obtain  $x_{\omega\Xi} = 0.3989$  for  $V_\Xi = -10$  MeV and  $x_{\omega\Xi} = 0.4643$  for  $V_\Xi = 0$  MeV.

The resulting EOS are displayed in Fig.3a) for the QMC, QMC $\omega\rho$  for different values of the coupling parameter and QMC with protons and neutrons only. We also include the empirical EOS obtained by Steiner *et al.* from a heterogeneous set of seven neutron stars with well-determined distances [19]. We conclude that the agreement of the theoretical EOS with the empirical one when hyperons are included in the calculation is defined by the hyperon-meson interaction and the  $\Lambda_v$  coupling, or, equivalently, by the symmetry energy. The QMC  $pn$  EOS agrees with the constraints. However, the inclusion of hyperons with the hyperon couplings obtained for the hyperon nuclear potentials taking  $V_\Lambda = -28$  MeV,  $V_\Sigma = 30$  MeV and  $V_\Xi = -18$  MeV makes the EOS too soft. Increasing  $\Lambda_v$  makes the EOS harder bringing the EOS closer to the constraints defined by the empirical EOS. This is easily understood with the help of Fig.4. Increasing  $\Lambda_v$  gives rise to a softer  $pn$  EOS at high densities and, therefore, hinders the onset of hyperons. So

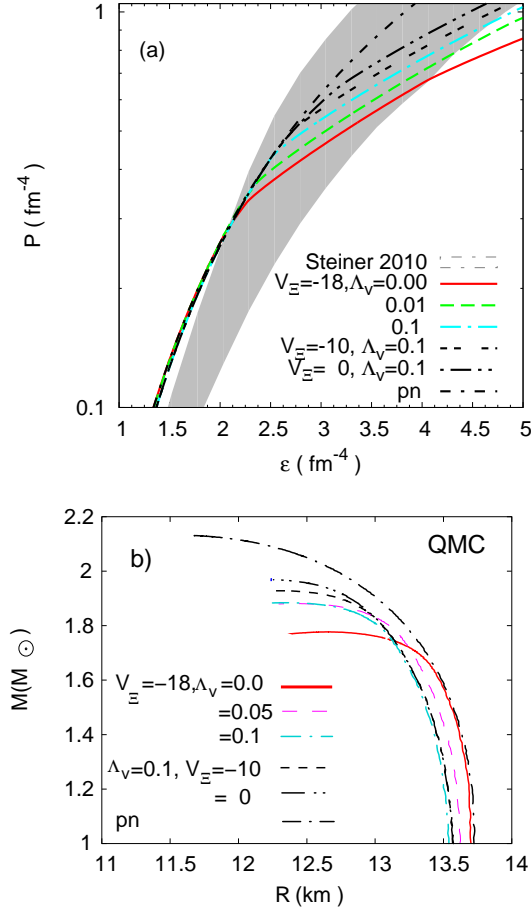


FIG. 3. (Color online) a) Equation of state and b) TOV results for QMC and QMC $\omega\rho$ . The EOS for  $V_{\Xi} = -10$  MeV and 0 MeV where only obtained with  $\Lambda_v = 0.1$ .

the larger  $\Lambda_v$  the smaller the hyperon fraction in the star and the harder the EOS.

The effect of a less attractive  $V_{\Xi}$  potential is also clear: the EOS becomes harder because the onset of hyperons occurs at larger densities as shown in Fig.4. We conclude that any mechanism that hinders the formation of hyperons makes the EOS harder.

The EOS enters as input to the Tolman-Volkoff-Oppenheimer [39] equations, which generate the macroscopic stellar quantities. The obtained mass/radius curve for stars with a mass larger than  $1M_{\odot}$  and the corresponding properties of maximum mass stars are then shown, respectively, in Fig.3b) and Table II.

First let us discuss the effect of the symmetry energy and the hyperon couplings on the mass/radius curve. A larger  $\Lambda_v$  gives rise to a softer EOS and, therefore, a smaller radius. It is seen that when going from  $\Lambda_v = 0$  to 0.1 the radius of a star with a mass  $M = 1 - 1.5 M_{\odot}$  decreases by  $\sim 0.3$  Km. This effect was already discussed within NLWM for nucleonic stars [6, 23] and for hyperonic stars [24]. In this last paper it was shown that there exists a clear correlation between  $L$  and star radius. How-

TABLE II. Stellar properties obtained with the QMC model and different values of the parameter  $\Lambda_v$  and the  $\Xi$ -meson coupling. *pn* stands for nucleonic matter with no hyperons included.

$\Lambda_v$	$V_{\Xi}$ (MeV)	$M_{max}(M_{\odot})$	$M_b(M_{\odot})$	R(km)	$\varepsilon_0(\text{fm}^{-4})$
0.0	-18	1.776	2.006	12.657	4.620
0.01	-18	1.836	2.096	12.496	4.837
0.03	-18	1.871	2.152	12.458	4.892
0.05	-18	1.880	2.170	12.415	4.945
0.1	-18	1.888	2.182	12.345	5.004
0.1	-10	1.928	2.243	12.292	5.113
0.1	0	1.969	2.301	12.218	5.182
0	pn	2.131	2.492	11.623	5.986

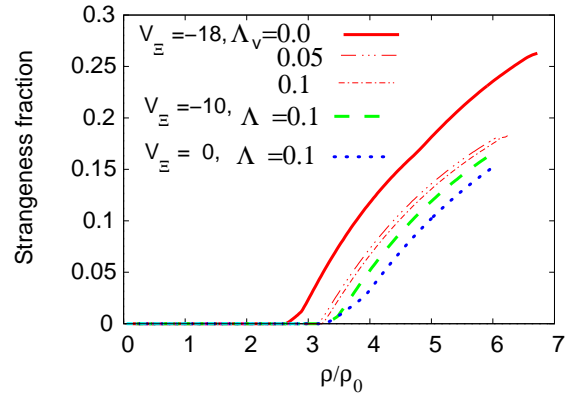


FIG. 4. (Color online) Strangeness fraction as a function of density QMC $\omega\rho$ . For  $V_{\Xi} = -10$  and 0 MeV we have taken  $\Lambda_v = 0.1$ , For  $V_{\Xi} = -18$  MeV, we show results for  $\Lambda_v = 0, 0.05, 0.1$ .

ever, within the models discussed in [24] the maximum mass did not to depend on  $L$ , while in the framework of the QMC model there is a clear effect of almost  $0.1M_{\odot}$  if  $\Lambda_v$  increases from 0 to 0.1. This is mainly due to the smaller strangeness fraction inside the star.

The reduction of the attractiveness of  $V_{\Xi}$  has a similar effect on the maximum mass of the star, i.e., the mass increases  $\sim 0.2 M_{\odot}$  if  $V_{\Xi}$  increases from -18 to 0 MeV.

We conclude that there is still quite a large uncertainty on the coupling of hyperons to nuclear matter and therefore, there is still room for a very massive star such as the recently measured pulsar J1614-2230 with a mass  $M = 1.97 \pm 0.04$  [18], even including hyperons in the EOS. This, however, is a particularly massive star. Most of the known pulsars [40] can be obtained by the present models.

#### IV. SUMMARY AND DISCUSSION

We have proposed a modified QMC model which includes a nonlinear  $\omega\rho$  coupling in the same fashion as it has been proposed for the NLMW [6]. In QMC model

the nucleons are described as non-overlapping bags. The extra contribution allows the softening of the symmetry energy at large densities. In NLWM or QMC without this term the symmetry energy increases almost linearly with the baryonic density giving rise to very hard stellar matter EOS. The inclusion of this term remedies this problem and brings down the slope of the symmetry energy at saturation density to values closer to the experimental predictions (see [7] for a compilation of all constraints on  $L$ ). With the modified QMC, we may take advantage of the already known good properties of the QMC together with a symmetry energy that is not too hard. We have also shown that the behavior of the modified QMC model is closer to the properties of nuclear relativistic models with density dependent couplings such as TW, a relativistic nuclear model with density dependent couplings [26]. Namely, the crust-core transition density is larger than the one predicted by the standard QMC and similar to TW and the distillation effect in non homogeneous matter does not increase with density as in NL3, but decreases as in TW.

We have also discussed the effect of the new EOS on the stellar properties. Hyperons were included in the EOS, and, for the hyperon couplings we took advantage of the fact that QMC predicts the hyperon effective masses without being necessary to fix the hyperon- $\sigma$  couplings. We have used information from hypernuclei to fix the hyperon- $\omega$  coupling and the hyperon- $\rho$  coupling was considered equal to the one of the nucleon. Since there

is a large uncertainty on hypernuclei with  $\Sigma$  and  $\Xi$ , we have also tested the effect of increasing the potential  $V_{\Xi}$  so that it becomes less attractive. It was shown that both the symmetry energy and the hyperon couplings have a strong effect on the mass and radius of the star. A softer symmetry energy gives rise to smaller stars. Also the hyperon fraction is affected: softer symmetry energy corresponds to a smaller hyperon fraction as already discussed in [24]. However, within QMC the density dependence of the symmetry energy has also an effect on the maximum star mass and this effect was not obtained in [24].

It was also shown that the hyperon nuclear interaction defines the amount of strangeness in the star, and, therefore, has a strong influence on the maximum mass allowed. Even including hyperons in the QMC EOS we could explain the mass of the pulsar J1614-2230 if the cascade nuclear potential is set to be very little attractive. More data on hypernuclei is needed to constrain the hyperon-meson couplings.

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